

GEOMORPHOLOGY OF THE VALLEY OF THE LITTLE COLORADO
RIVER, ARIZONA

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ABSTRACT

The Little Colorado River, a tributary from the southeast, empties into the Colorado River at the head of the Grand Canyon. It drains an extensive desert area in northeastern Arizona. Upstream from a gorge 60 miles long in the Marble Platform it flows in a broad valley which is the subject of the present study. The stratigraphy, structure, and volcanic rocks are summarized in a geologic map as a basis for the geomorphic study.

Three successive erosion surfaces are, from highest to lowest, the Black Point pediplane, the Wupatki pediplane, and the Little Colorado pediplane. Each is interpreted as having formed during a period of stability of the profile of the Little Colorado River. It is concluded that the Black Point and Wupatki pediplanes represent the culmination of long periods of erosion, each interrupted and rejuvenated by regional uplift. During the formation of the present Little Colorado pediplane, the stabilization of base level has been controlled by the occurrence of resistant beds along the course of the master stream.

The history of the Grand Canyon of the Colorado has been postulated by previous writers to consist of two great cycles of erosion. The events of the valley of the Little Colorado are interpreted as having taken place during the second of these, "the canyon cycle". The Black Point pediplane was well developed at the time of Stage 1 lavas which are of uppermost Pliocene or early Pleistocene age. The Wupatki pediplane was formed prior to Stage 2 lavas which are of early or middle Pleistocene age. The Little Colorado surface is still in the process of development and is found locally beneath Stage 3 and Stage 4 lavas.

INTRODUCTION

OBJECTIVES OF THE STUDY

The valley of the Little Colorado River in north-central Arizona is one of the colorful highly elevated deserts of the Southwest. The entire region is subject to

the vigorous attack of erosion, and bare rock slopes cut by deep arroyos are seen everywhere. The study of surface features must concern itself primarily with processes and effects of active degradation, for stream depositional features are only local and transitory. The constructional features are mostly volcanic in origin, and they occur mainly along the western part of the valley as the eastern periphery of the San Francisco volcanic field. Lava flows of various thicknesses are common. Basaltic cinder cones, cinder-sand dunes, and extensive sheets of cinders and ash abound, and all show remarkable linear arrangement from southwest to northeast, which is the prevailing wind direction. Depositional features are subordinate to the general erosional forms of the region.

The principal erosional process is clearly stream wash, and in this arid climate the process is active only during the irregular periods of intense rainfall. The Little Colorado River acts as base level for its tributaries. Several resistant strata outcrop in the valley, and locally *cuestas*, canyon zones, strip slopes, and mesas attest the resistance to erosion. Past surfaces of erosion appear as gently inclined summits in interfluvial areas. Many remnants of erosion surfaces truncate hard and soft beds alike and are seen at successive levels.

The main objectives of the present study are: (1) to describe the different erosion surfaces, (2) to determine the factors that controlled their development, (3) to date them, and (4) to fit the sequence of events in the valley of the Little Colorado as far as possible into the geomorphic events of the region.

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GEOGRAPHY

LOCATION OF THE AREA

Detailed field work in the valley of the Little Colorado from Leupp downstream to Cameron provided data for geologic and geomorphic maps. Reconnaissance study extended beyond the mapped area (Fig. 1).

The area of detailed study is readily accessible from main highways. U. S. Highway 66, into Flagstaff, crosses the southwestern corner of the area and branch roads reach to the river downstream from Leupp at Grand Falls and pass through Leupp en route to the Hopi Villages in the highlands of Black Mesa. From Flagstaff to Cameron, U. S. Highway 89 crosses the northwestern corner of the area, and a branch road runs eastward to the Indian ruins at Wupatki National Monument and to the Little Colorado River.

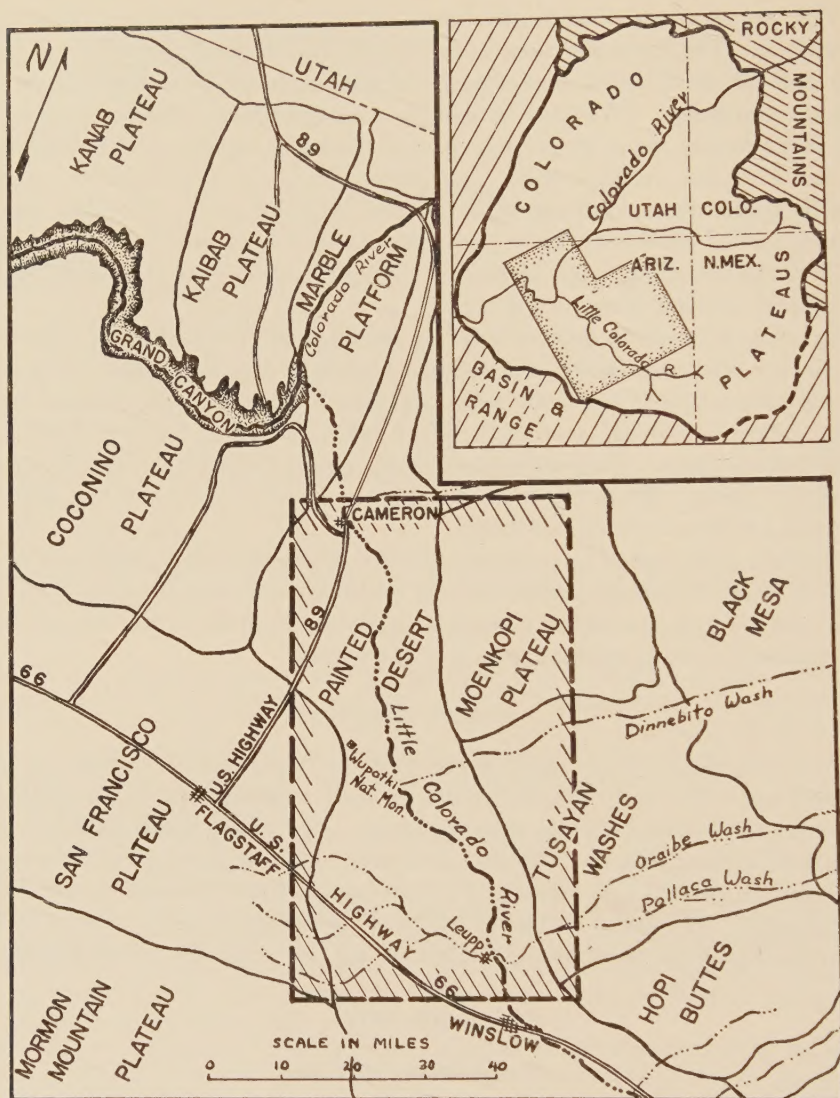


FIGURE 1.—Index map

Showing locations of geologic map (Pl. 1) and geomorphic divisions (Pl. 4). Small map in upper right shows general location of area.

TOPOGRAPHY AND DRAINAGE

The valley of the Little Colorado River trends generally northwest from Leupp to Cameron. At Leupp the valley is approximately 12 miles wide. From the river at an elevation of 4700 feet the general surface rises steadily to the west and in 40 miles reaches the summit of the San Francisco Plateau at 6800 feet. The San Francisco volcanic peaks rise abruptly above the plateau surface to elevations greater than

12,000 feet. Eastward from the river the surface rises gently to the foot of the colorful Chinle cliffs, then over a series of steplike cliffs to the distant plateau highlands of Black Mesa.

The gradient of the Little Colorado River is not constant. From Leupp to Cameron it increases from 4 to 7 feet per mile, and the valley becomes more and more constricted, with the broad river flats giving way to narrow canyons. A short distance upstream from Cameron the river enters a narrow gorge in which it continues for 54 miles, while descending 1600 feet to join the Colorado. The surface of the Marble Platform, through which the gorge is cut, rises steadily so that, at its junction with the Colorado, the Little Colorado issues from a canyon 3500 feet deep.

The Little Colorado is the master stream of an extensive watershed that drains the southern part of the Colorado Plateaus into the Colorado River. The actual flow of water in the entire drainage system is limited to two general periods during the year. Melting snow in the highlands feeds the drainage lines in spring and early summer. The late summer "rainy" season, a period of local storms and cloudbursts, results in the maximum flow of the streams. Highlands west of the Little Colorado are drained by numerous short streams with fairly steep gradients. The longest and largest tributary channel from the southwest is that formed by the uniting of Walnut Creek, Padre Creek, and Diablo Creek. These streams begin on the San Francisco Plateau and, after merging, flow into the Little Colorado at Leupp. From the northeast the master stream receives the long tributaries of Dinnebito Wash, and Pollaca Wash. These two great intermittent stream channels drain the highlands to the northeast and reach back 90 miles into the dissected plateaus of the Navajo country. From the north another such tributary, Moenkopi Wash, enters the Little Colorado just downstream from Cameron.

CLIMATE AND VEGETATION

Along the floor of the valley of the Little Colorado one of the hottest and driest climates of southwestern United States prevails.

The Painted Desert, part of which is included in the area of this report, is a highly elevated desert; thus, the diurnal and yearly range of temperature is great. The elevation of the valley floor here ranges from 4100 to 4800 feet and summer maximum temperatures of 105° F. are not uncommon. The diurnal range is often 50° F. High elevation also slightly increases the amount of precipitation. Thornthwaite, Sharpe and Dosch (1942) point out that for over 9 years there has been an average of 30 days each year with rain at Leupp. Further, in the 13 years of weather recording, the maximum rainfall of 9.09 inches was recorded in 1915. The minimum record of 2.52 inches was recorded in 1938. They note also that the maximum rainfall at Leupp is less than the maximum recorded at any of the other 38 stations in northern Arizona. The general precipitation pattern for most of Arizona and western New Mexico is that of a rainy winter and late summer, with a dry late spring and autumn.

Late summer is the principal wet season and, although a few general rains involve large areas, the most common summer rains are localized heavy thunderstorms of short duration. A common and interesting experience is that of watching a storm

occur aloft with the rain evaporating before reaching the ground. During the wet season intense storms may occur for short periods, and the dry washes suddenly become choked with muddy torrents. Only a relatively small increase in elevation provides a marked increase in rainfall and associated lower temperatures.

STRATIGRAPHY AND PETROLOGY

GENERAL CHARACTER AND DISTRIBUTION

The valley of the Little Colorado River from Leupp to Cameron exposes Permian, Triassic, Jurassic, and Late Tertiary rocks. The Permian layers are sandstones, cherty limestones, and dolomites of the Kaibab formation. The Triassic includes the red sandstones, shales, conglomerates, gypsum, and variegated shales of the Moenkopi, Shinarump, and Chinle formations. The Jurassic includes the massive sandstones, and shales of the Glen Canyon group. The late Tertiary rocks comprise a series of basaltic lavas in large part blanketed by an extensive covering of basaltic ash and cinders. Also, numerous deposits of well-rounded, weathered, and unconsolidated gravels cap remnants of pediments. The gravels are commonly 6 to 8 feet thick but in places reach 20 feet. They consist largely of the resistant types of rock of all the older formations.

In this region, as in most of the plateau country, the general horizontality of the beds, their deep dissection, and the sparsity of vegetation facilitate stratigraphic studies. Some of the earliest geologic work in the West included a general classification and dating of the section in the Little Colorado River Valley. In Ives's (1861) report, the valley of the Flax River (Little Colorado) was described, and the "Carboniferous" rocks with younger shales and marls were noted. Later brief visits by the geologists of the Wheeler Survey in 1875 added stratigraphic details. Since 1900 Ward (1901), Gregory (1917), McKee (1938), and others have studied the formations of the area in considerable detail.

A geologic map (Pl. 1) of the Leupp-Wupatki-Cameron area along the Little Colorado River was made by using the photographic mosaics of the Soil Conservation Service. Each controlled mosaic covers an area of 15 minutes of longitude and latitude at a scale of an inch to the mile. Sedimentary contacts and the limits of lava flows were located, examined in the field, and traced upon the mosaics. The area west of Longitude $111^{\circ} 20' W.$ was taken largely from a geologic map prepared in a similar manner by Babenroth and Strahler (1945). The region west of Long. $111^{\circ} 20' W.$ and south of Lat. $36^{\circ} 25' N.$ was adapted from a map drawn from aerial mosaics by H. S. Colton as a continuation of his work in Bulletin 10 of the Museum of Northern Arizona.

KAIBAB FORMATION

Gilbert (1875) included the Kaibab formation as the upper 200 to 220 feet of his Aubrey group. Darton (1910) subdivided the Aubrey group into three formations: the Kaibab limestone (including the present Kaibab and Toroweap), the Coconino sandstone, and the Supai formation (the present Hermit and Supai). Noble (1928) described a complete section of the Kaibab limestone in the deep canyon of Kaibab

Gulch. This tributary gorge runs into the Colorado River just north of the Arizona State line, and it is recognized today as the type section for the Kaibab formation.

Beds of the Permian Kaibab formation are extensively exposed along the western side of the Little Colorado Valley. Where erosion has cut through the resistant Kaibab, the valleys are gorge-shaped. Along the course of the Little Colorado, and to the west, local structures have so raised the Kaibab that nearly barren strip surfaces are particularly conspicuous. Farther west the Kaibab formation rises and forms the surface of the highest topographic elements of the region, namely, the San Francisco, the Coconino, and the Kaibab plateaus.

Downstream approximately 11 miles from Leupp, the Little Colorado enters a steep-walled canyon which continues for 16 miles to Black Falls. The abrupt walls reach a maximum height of 200 feet and expose a complete section of the Kaibab formation (Pl. 2, fig. 1). Beds of yellow to white limestone, and sandy limestone with nodules of chert occur from top to bottom, but half the total thickness is made up of calcareous yellow and red sandstone. The Kaibab rests on a white cross-bedded sandstone, 4 feet of which is exposed in the bottom of the gorge. McKee (1938) has divided the original Kaibab into the Kaibab (upper) and Toroweap (lower) formations. The lower 4 feet of white sandstone seen in the canyon at Grand Falls may be the top of the Toroweap. McKee believes that the Kaibab formation thins eastward from the Grand Canyon and is a near-shore facies along the Little Colorado River.

The Permian strata are the oldest exposed in the area of this study.

MOENKOPI FORMATION

The Moenkopi is the lowest of the thick Mesozoic formations that lie with hardly perceptible unconformity on the Kaibab. These Mesozoic strata were first studied by Ward (1901) who named them the "Moencopie beds", and recognized that they lie unconformably on the "Carboniferous Upper Aubrey" (Kaibab). In later regional studies Gregory (1913; 1917) identified the age as Permian, based on fossils found and identified by Walcott from the Kanab Valley, Utah. More recently, Baker and Reeside (1929), have reported the Moenkopi formation as Lower Triassic, and at least in part of marine origin. It is so held by most of the present workers in the area.

In the area of this study, the section of red sandstones and shales of the Moenkopi formation is best seen west of the river. The Little Colorado River is bedded in the Moenkopi, for the most part midway between the lower and upper contacts. Along the western side of the river the Moenkopi is much dissected, and the contact with the underlying Kaibab is very irregular. Here, the Moenkopi makes up numerous island like erosion remnants that are wasting away rapidly on a floor of resistant Kaibab.

In the sections measured, the Moenkopi formation ranges in thickness from 336 to 350 feet. The base of the formation contains a few lenticular conglomerates of limestone, chert, and sandy limestone. Proceeding upward in the section there are: an interbedded series of red shale and thin limestone beds, red and white shale with selenite layers, finely laminated white shale and red shale, and massive red sandstone

and shale layers replete with ripple marks and mud cracks. An uppermost zone of 22 feet is remarkably persistent. It is made up of two members—a fissile red shale criss-crossed with calcite veins, and a massive, cross-bedded, red sandstone.

SHINARUMP AND CHINLE FORMATIONS

Gilbert (1875) named the Shinarump conglomerate and dated it as Triassic. Gregory (1913) pointed out its persistent character over large areas throughout the Colorado Plateau province in Utah, Arizona, and New Mexico. The thickness ranges from 20 to 382 feet, but over large areas it is somewhat less than 100 feet. He considered it to be the base of the Triassic system, since he considered the underlying Moenkopi to be Permian. He recognized a slight unconformity at the base of the Shinarump but found the bedding conformable upward into the overlying shales and marls of the Chinle formation.

Today, the Moenkopi is considered Lower Triassic, the Shinarump is held as Upper (?) Triassic and at the base of the undoubted Upper Triassic beds of the Chinle (Gregory, 1917). Its type locality is in the Shinarump cliffs south of the Vermillion cliffs in Kane County, Utah.

Along the eastern side of the valley of the Little Colorado the Shinarump conglomerate is only 26 to 50 feet thick and commonly forms a resistant cap rock of cuervas. Usually the base of the cuesta is of Moenkopi, and, as at Black Falls, the crest is 150 to 200 feet above the river. Locally, there is some variation in the size of pebbles of the conglomerate and in the strength and degree of cementation. This results in an irregular resistance to erosion and renders variable the cliff-forming habit of the formation.

The usual lithology includes a lower zone of red cross-bedded sandstone with chert pebbles nearly an inch in diameter, and with clusters of black ferruginous concretions. Above these beds are fine-grained, white, cross-bedded sandstones and coarse red sandstones with bean-sized black concretions.

The Chinle formation of Upper Triassic age was originally described by H. E. Gregory (1916) from the Chinle Valley of northeastern Arizona. The formation varies in thickness from 400 to 1000 feet throughout the Colorado plateaus. Details of its lithology and stratigraphy have been described by many workers in the Plateau Province.

The brilliantly colored beds of the Chinle may be seen along the eastern flank of the Little Colorado River Valley making up the steep west-facing front of a long, somewhat continuous cuesta ridge. The layers of variegated shales with only a few resistant beds have made the formation weakly resistant to erosion. Hence, the retreating cuesta front stands at the head of a long well-developed pediment that slopes gently toward the Little Colorado. The Chinle formation in this region ranges from 500 to 575 feet in thickness and consists of a lower group of beds approximately 200 feet thick that predominate in shales with colors of buff, gray, blue, chocolate, red, purple, and white. There is a central zone, 50 feet thick, of sandstone and conglomerate made up of buff and gray sand rich with inclusions of chert and quartzite pebbles, as well as numerous fragments of petrified logs. The upper group of

strata, 300 feet or more thick, exhibits a greater number of limestone, bedded chert, conglomerate, and sandstone beds interlayered with shale, the predominant rock. The numerous resistant beds in the upper part of the formation commonly make cliffs in this part of the section. In the upper zone the colors continue to vary through gray, buff, red, purple, blue, and white.

The top of the Chinle formation contains beds of red sandstone and shale more thinly bedded, and usually of finer texture than the massive overlying formations of the Glen Canyon group. In the area of this study, the contact with the Glen Canyon seems conformable, but Gregory (1917) concludes from his studies in other areas that there is ample evidence to indicate not only a break in sedimentation, but an erosional interval.

GLEN CANYON GROUP

The Glen Canyon group includes the Wingate sandstone, the Kayenta formation (originally the Todilto sandstone), and the Navajo formation. It is considered to be Lower Jurassic (?). The Wingate formation appears as a massive red sandstone cliff east of the Little Colorado River. The escarpment is 16 miles northeast of Leupp and 9 miles east of the river at Cameron. The massive cliff-making formations of the Glen Canyon group stand as steplike benches that extend far back into the eastern drainage area of the Little Colorado.

BASALTIC LAVA FLOWS

Character and distribution.—Basaltic lava flows of the eastern and northeastern periphery of the San Francisco volcanic field extend into the region immediately west of the Little Colorado River. Here they are associated with erosional features and may be related to the sequence of geomorphic events.

Robinson (1913) established three general periods of volcanic activity in the San Francisco volcanic field. The first, in late Pliocene, was characterized by widespread eruptions of thin basalt flows largely from local vents and in part from fissures. During the second more intense period, approximately 56 cubic miles of lavas was erupted, ranging from andesite to rhyolite, and laccoliths were intruded. During this second period such high topographic features as the San Francisco Peaks and Sitgreaves, Kendrick, and Bill Williams peaks were formed. Most of the peaks are made up of two or more types of lavas ranging from acidic to intermediate in composition. The third period was again one of basaltic extrusion. The lava this time was somewhat more viscous than that of the first period and the flows are thick and of lesser extent. Two hundred or more basaltic cinder cones were formed with a somewhat uniform distribution over the whole volcanic field, except east of the San Francisco peaks where they are particularly abundant.

Robinson's (1913) first and third period lavas include all the basaltic flows along the western flank of the valley of the Little Colorado. His chemical analysis and studies of numerous thin sections showed a "decidedly uniform mineral composition . . . an equally uniform chemical composition" of first and third period basalts. All the lavas in the area of the present study were strikingly similar megascopically

and seem to emphasize Robinson's (1913) statement that "each period (first and third) is represented by a single lava—a typical basalt—of uniform composition."

Colton (1937) developed a useful chronologic classification of basaltic flows and cinder cones in the San Francisco area based on the degree of weathering and erosion. The determination of the relative age of flows is not always easy. The older flows cannot be traced any great distance. Locally they are covered by cinder deposits or are hidden beneath younger lavas. Only the youngest flows can be traced with confidence. In some places old flows stand isolated as the resistant caps of mesas. Young flows in some places reach beyond the limits of older ones and spread over sedimentary layers at a lower level than the old lavas. Neither megascopically nor microscopically have the successive flows of basalt shown characterizing differences. Stratigraphic position and elevation of the flows must be considered with caution, and chief reliance for age determination must be placed on the relative amounts of weathering and erosion of the lavas, and of the surfaces over which the lavas flowed.

Colton's (1937) work was primarily directed toward greater detail regarding the cinder cones and lava flows of Robinson's third period of volcanic activity. He mapped the distribution of 388 cones and the outlines of lava flows. Characteristic criteria were set up for each of five stages of cones and flows. Since the successive age relationships are best shown on the northern and eastern periphery of the lava field, it is in this area that Colton's five stages are described.

The correlation chart (Table 1) illustrates the relationship of Robinson's (1913) lavas of the San Francisco field, the peripheral stages recognized by Colton, and the stages recognized in the area of this report.

Stages 1 and 2.—The basaltic lavas of Stages 1 and 2 have been subjected to a long period of weathering and erosion and look much older than the later lavas. The original extent of the flows cannot be recognized due to the erosional retreat of the edges, and through weathering the original lava surface is nearly gone. Aa and pahoehoe textural structures, as well as buckled pressure ridges and spatter cones, are all but lost on the relatively smooth surfaces of both Stage 1 and Stage 2 lavas.

Colton (1937) believes that Stage 2 flows show (1) relatively more traces of pressure ridges and spatter cones, and (2) evidence of deeper erosion of the floor over which the lavas spread. These features, together with superposition of Stage 2 lavas on Stage 1 wherever it could be demonstrated, were used in classifying the flows.

Age differentiation of lavas in the area of this study can be made with even more assurance. A sequence of pediments exists along the Little Colorado River and the different ages of the surfaces over which the lavas flowed provide a most satisfactory basis for separating Stage 1 from Stage 2. Stage 1 lavas are on the highest and oldest pediment where they have preserved an erosion surface that truncates shale and sandstone beds. Stage 2 lavas are found locally on a younger and lower pediment surface. The basaltic lavas of both stages have been so weathered and eroded that the original surface structures are nearly lost. The position of lava flows on erosion surfaces of different age further indicates a long interval or erosion between the two periods of extrusion. Since the lava flows of Stages 1 and 2 are often masked by cinders or younger flows, the relation to successive pediments is very helpful.

Stage 3.—Spatter cones and buckled pressure ridges, although somewhat subdued by weathering, identify Stage 3 lavas readily. The flows of Stage 3 are quite widespread and characteristically are 60 to 90 feet thick—much thicker than the older and younger flows. The fronts of the flows are serrate due to the headward extension of numerous gullies.

TABLE 1.—*Correlation chart of the San Francisco lavas*

Colton (1937)	Robinson (1913)	Present Paper	
Erosion	Erosion 3d period. Volcanic activity intermittently during uplift and "canyon cycle" of erosion	Erosion	Present
5th State		4th Stage	
4th Stage		Erosion	
3d Stage	2d period of volcanic activity; occurred during wide-spread stripping and erosion. (acid lavas and intrusions)	3d Stage	Pleistocene
		Erosion	
2d Stage*		2d Stage	
1st Stage	Erosion	Erosion	Late Pliocene
	1st period of volcanic activity	1st Stage	
	"Great denudation"	Erosion	

* It is not clear whether Colton's second stage lavas were formed prior to Robinson's second period (acidic lavas) or subsequent to them.

Colton recognizes periods of time between his lava stages, but since he presents no chart of this type, no attempt is made here to represent those intervals.

The surface of the lava is still rather rough, although the scoriaceous structure is largely obliterated by weathering. An indication of the recency of these lavas with reference to the present topography is well shown 9 miles northwest of Leupp. Here a Stage 3 flow followed down through a steep-walled canyon and nearly reached the Little Colorado River. The tributary was cut down into the resistant Kaibab formation, and thus the lava flow follows a stream channel that was entrenched as a result of the last rejuvenation of drainage.

Stage 4.—The Stage 4 lavas are very fresh looking. Lava surfaces are extremely rough and very little affected by weathering. Common features are fresh spatter cones, buckled pressure ridges, and "cock's combs" where lava has squeezed up

through cracks like heavy grease. Very little or no gullying has developed around the edges of the flows. Where the flows extend beyond the limits of older lavas, they seek out the drainage channels leading to the Little Colorado.

In a flow of this stage at Grand Falls, the lavas found the river flowing in a rather narrow canyon some 200 feet deep (Pl. 2, figs. 1, 2). A thick lava dam was formed, and a flow 10 to 15 feet thick continued down the Little Colorado floor for 12 miles. For the most part the floor of the present channel is only slightly lower than the one over which the lava flowed, and the recency of the lava in the history of the river can be readily appreciated.

Colton (1937) has described a very recent Stage 5 lava associated with Sunset Crater, 20 miles west of the area of this study, approaching the San Francisco Peaks. These last flows are dated by archeological evidence as having occurred about 875 A.D.

CINDER CONES AND OTHER DEPOSITS

The San Francisco volcanic field contains a great number of volcanic cones. Many of the smaller cones, composed mainly of basaltic cinders, lapilli, and bombs, reach a height of 1000 feet. Cinder cones are particularly well developed in the eastern part of the field and are found in all stages of preservation. To Colton the amount of erosion and weathering of the cones is a key to a general classification and a suggested correlation with the successive lava stages. The correlation is most reliable in stages 4 and 5 because some of the lava flows can be traced to their source at the base of a cone.

The effect of wind on cinder cones and cinder-sand dunes is evident in many places. The prevailing wind direction is from the southwest to the northeast, and a resultant elongation is expressed in the cinder-cone profiles and in the position of dunes. An example of the effect of wind upon crater shape is seen at Merriam Crater (Pl. 1). Along a southwest-northeast cross section this great cinder cone is decidedly asymmetrical. The windward slope is very steep, approaching the angle of repose. The rim of the funnel-shaped crater at the crest of the cone is highest on the northeast side, and the leeward slope of the cone is inclined gently to the northeast.

Northeast edges of table lands are the sites for the accumulation of thick cinder deposits that slope downward steeply from the edge of the mesa. Ledges that face into the wind often have material deposited in front of them until slopes are formed up which the wind can roll cinders onto the highland beyond. These interesting fixed dunes usually form a segment of a cone with the apex in a notch in the ledge. The cinder deposit on the leeward side of the ledge has a steeper slope and is a more common deposit. Cinder deposits are found over lava flows of all stages, often masking the lava under a cover that tends to maintain a flat uniform surface over an irregular floor. The effect of such a porous cover greatly limits the amount of stream runoff; therefore, the headward growth of the gullies into the edges of lava flows, and into pediments so protected, is very slow. Below an elevation of 5500 feet vegetation becomes rather sparse, and wind transportation is most active. Above that elevation an increasing vegetation cover limits more and more the effectiveness of the wind.



FIGURE 1.

LOOKING NORTHWARD DOWNSTREAM FROM LAVA DAM AT GRAND FALLS

The river enters from the right and plunges over falls. Beds are Kaibab, lava in the foreground and to the left.



FIGURE 2.

LOOKING SOUTHWARD UPSTREAM FROM GRAND FALLS

Sediment-filled canyon behind lava dam. Note cinders in the foreground and along the (leeward) west canyon wall in the background.



FIGURE 1.

LOOKING NORTHWARD FROM SUMMIT OF MERRIAM CRATER

1. Stage 1 lavas capping a remnant of the Black Point pediplane, 2. Part of the Wupatki pediplane, 3. Stage 3 lavas, 4. Black Point, 5. Coconino Point and the Coconino plateau.



FIGURE 2.

VIEW IS EASTWARD FROM DONEY CRATER

W, Wupatki pediplane beneath Stage 2 lavas; BP, Woodhouse Mesa remnant of Black Point pediplane under Stage 1 lava; B, Interfluve remnants of the Wupatki "B" pediplane.

GEOLOGIC STRUCTURES

GENERAL CHARACTERISTICS

Nearly horizontal beds over large areas with local high-angle faults, sharp monoclines, and anticlines characterize the Colorado Plateaus. Most of the faults and folds of the province fall into two general age groups. Laramide structures include the broad domes, basins, sharp monoclines, and the anticlines of the eastern part of the province. The great high-angle faults, mainly in the western part of the province, occurred in the middle and late Tertiary.

The principal structural features east and southeast of Grand Canyon are represented in Figure 2. The East Kaibab monocline and its branches make up the dominant structure of the region, and to the east is the less imposing Echo monocline. East of the San Francisco Plateau a local reversal of dip results in the gentle Tolchaco anticline.

WESTERN PLATEAUS

The San Francisco, Coconino, and Kaibab plateaus extend along the western margin of the valley of the Little Colorado River and continue north and south well beyond it. The Kaibab formation forms the surface of the plateaus where it is 2000 to 3000 feet above its position at the river (Fig. 2).

The San Francisco Plateau is a great flat-topped structural dome crowned with volcanic cones and lava flows. U. S. Highway 66 ascends to the summit of this plateau in approaching Flagstaff from the east. In 30 miles the Kaibab formation rises steadily 2000 feet to the top of the plateau. Farther north along the eastern flank the plateau is buried beneath lavas and cinder cones. In front of the lavas the beds are arched up gently to form the Tolchaco anticline. Still farther north the Mesa Butte and Black Point monoclines emerge from beneath the lava cover. The summit of the plateau on sedimentary rocks is approximately 6800 feet above sea level. Here the Kaibab formation is the floor on which the Tertiary volcanics accumulated. However, at the town of Flagstaff, Moenkopi beds are exposed beneath the lava capping. The Kaibab beds dip gently to the north from the plateau summit, giving the northern and northeastern section a gentle domelike structure steepened locally by marginal folds.

The Coconino Plateau is that part of the nearly flat highland bordered on the north by the Grand Canyon and on the east by the East Kaibab monocline. From the rim of Grand Canyon at 7000 feet, the beds and the plateau surface are inclined southward at about 100 feet per mile. To the south this inclination gradually flattens and is reversed as the beds ascend toward the San Francisco Plateau. Thus, there is developed a broad saddle, hardly preceptible to the eye except as a skyline profile and best shown by drainage channels. The northeastern corner of the Coconino Plateau is depressed 600 feet below the general surface by the Grand View monocline, where it branches northwestward from the East Kaibab monocline and reaches across the corner of the plateau into the Grand Canyon. This depressed area is called the Upper Basin and is bordered by the Grand Canyon on the north,

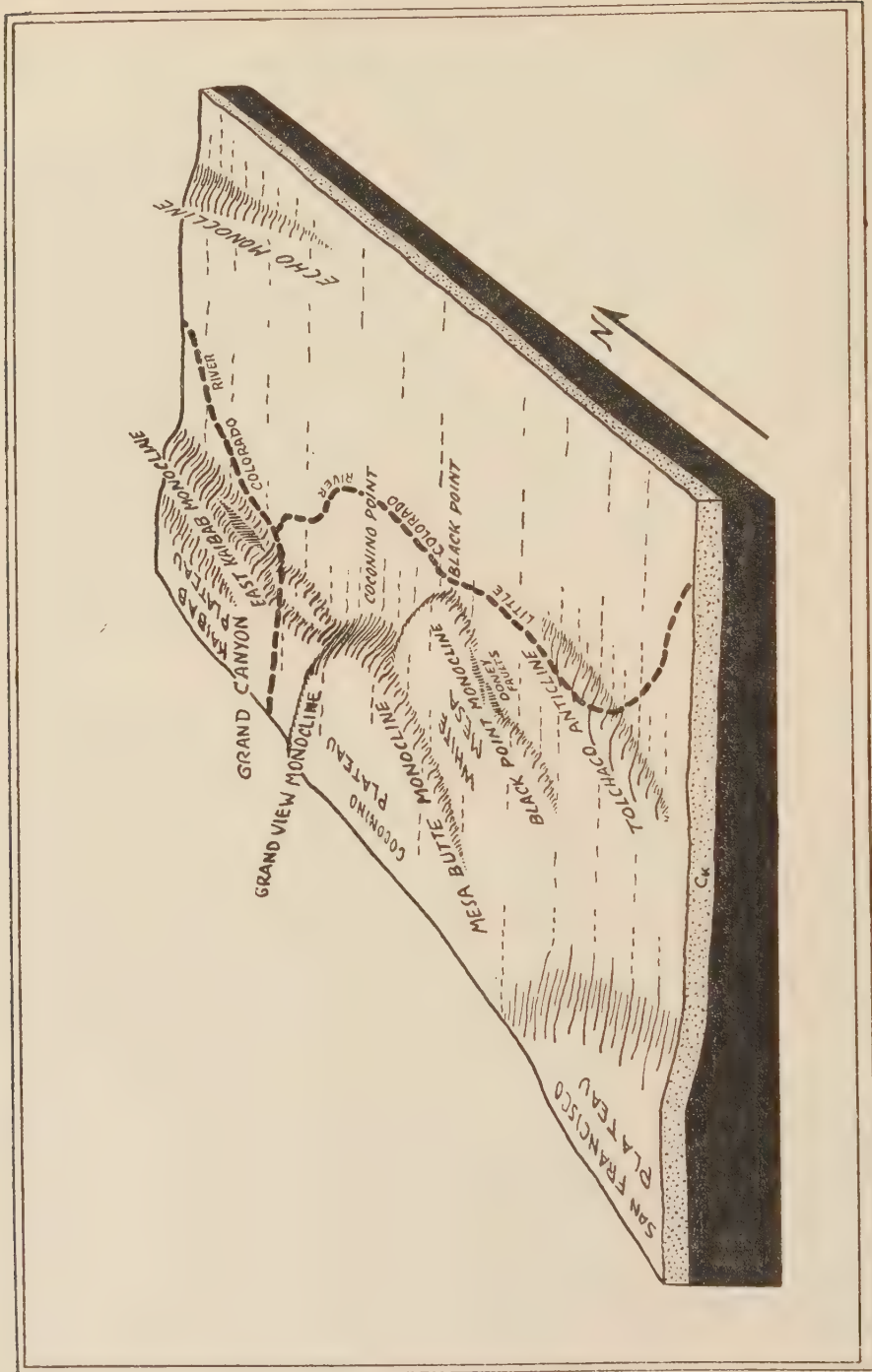


FIGURE 2.—Diagram of regional structural features

the Grand View monocline on the west and south, and the East Kaibab monocline on the east.

The highland north of Grand Canyon is the Kaibab Plateau, bordered on the east by the East Kaibab monocline. The Kaibab is the highest and easternmost of the group of plateaus through which the Colorado River has carved out the Grand Canyon. The general structure of the Kaibab Plateau is that of an elliptical dome with the long axis trending north. The Kaibab formation forms the surface of the plateau, and the beds continue in the same attitude as in the Coconino Plateau across the canyon. Northward from the North Rim of Grand Canyon the beds and the plateau surface rise 100 feet to the mile, from 8000 feet elevation over the flat crest of the dome at 9000 feet. Opposite this highest portion of the plateau the beds descend to the east over a double monocline fold.

MONOCLINES

The dominant structure of the region is the East Kaibab monocline. Sections of this great flexure have been described as parts of numerous regional studies in the plateau province. It was named by Powell (1875). Recently, Babenroth and Strahler (1945) have studied it as a structural unit and have described it in detail from the southern terminus under the San Francisco lavas to its northern end east of Bryce Canyon, Utah. Throughout this general north-south trend of 150 miles it is downthrown to the east reaching a maximum of 5000 feet.

The monocline is doubled along the eastern flank of the Kaibab Plateau, and the beds descend 3000 feet in two steps from the top of the plateau to the Marble Platform. Opposite the junction of the Little Colorado and the Colorado rivers, and north of the Grand Canyon proper, the monocline becomes in part a fault whose displacement is 2000 feet. Additional drag gives a total displacement of 2700 feet. This is the Butte fault, and it represents a section of the monocline that has broken. However, to the north and south the fault gives way to a true monocline fold. The fault is approximately 15 miles long.

South of Grand Canyon the East Kaibab monocline consists of four distinct branches radiating from the highest point in the region, Coconino Point. Here the displacement due to the fold reaches a maximum of 2300 feet in a horizontal distance of a mile. Babenroth and Strahler (1945) point out a fault midway on the monocline limb, with its strike following that of the fold as it swings around Coconino Point. Throw of the fault is opposite the displacement of the fold and reaches a maximum of 200 to 300 feet. Northwestward 6 miles from Coconino Point the displacement along the monocline decreases to 1200 feet. Here, the fold divides into two branches of equal throw, which trend nearly at right angles to each other. One branch swings to the west, and the other to the north (Fig. 2). The west branch is the Grand View monocline which continues westward 6 miles, then northwestward into the Grand Canyon where it dies out. The branch that runs northward becomes a double monocline for a short distance. The displacement is increased to 900 feet at Grand Canyon and continues northward as the section of the East Kaibab fold already described. Southward from Coconino Point the

displacement of the monocline decreases to 1500 feet where it branches again nearly at right angles (Fig. 2). The Mesa Butte monocline continues to the southwest, decreasing in throw gradually from a maximum of 750 feet. It dies out east of the saddle between the Coconino and the San Francisco plateaus. The Black Point monocline is a very gentle fold at its junction with the more abrupt Mesa Butte branch, but to the southeast the dip reaches 20° , and the displacement increases from 600 to 1000 feet just north of Black Point. The fold swings around Black Point changing its trend to southwest. Five miles southwest of Black Point the steep monoclinical fold breaks into a fault which continues for 3 miles until it disappears beneath the lavas and cinder cones of Doney crater. Beyond the crater to the southwest, the monocline continues $2\frac{1}{2}$ miles before disappearing beneath the San Francisco lava flows.

Babenroth and Strahler (1945) believe that the East Kaibab monocline was probably produced in a single period of flexing of Laramide or early Tertiary date. This age is shown clearly in the area of Canaan Peak, Utah, near the northern end of the fold, where Eocene beds lie unconformably on folded Cretaceous beds. However, stratigraphic evidence is lacking for dating of deformation along the middle and southern parts of the monocline.

The Echo Cliffs face westward across the Marble Platform opposite the Kaibab Plateau. The west-facing escarpment is cut in Mesozoic rocks and stands near the axis of a monocline which folds the beds down to the east. Thus, the topographic expression of this monocline is exactly opposite to that of the East Kaibab monocline. The Echo monocline has much less displacement than does the Kaibab to the west, and it dies out north of the Little Colorado River.

TOLCHACO ANTICLINE

The Tolchaco anticline is a low, gentle fold extending northeastward from U. S. Highway 66 to Dinnebito Wash (Pl. 1). It is asymmetrical at its southern end but becomes more symmetrical to the north. The axis of the fold trends north-northeast throughout most of its 24-mile length. Northeast of the Santa Fe Railroad crossing of Diablo Creek, the Kaibab beds at the surface lose their regional dip as the fold takes form. Diablo Creek crosses the axis where the fold is not pronounced and continues parallel with the axis of the fold to the junction with Padre Creek. Padre Creek approaches the fold from the west, flows southwestward across the axis and eastward to the junction with Diablo Creek. The western limb dips 10° , and the eastern limb 5° . The maximum structural relief of the fold is approximately 200 feet. To the north the slightly asymmetrical character is not pronounced as the fold continues obliquely across the path of the Little Colorado River. Downstream from the old mission site of Tolchaco the Little Colorado enters a canyon zone where the anticline raises the top of the Kaibab formation above the gradient of the river. This canyon zone continues for 16 miles across the fold at a very small angle to the axis. Evidence of the fold is lost north of Dinnebito Wash where the beds resume their eastward regional dip of 3° . Closure, if it exists at all in the Tolchaco anticline, is less than 100 feet.

GRABENS

Apart from the faulted monoclinal limbs numerous single faults and elongated graben trenches have been mapped. Babenroth and Strahler (1945) show 24 grabens resulting along faults with marked displacement. The grabens shown by these authors occur mostly on the Coconino Plateau, along the Little Colorado River east and northeast of Coconino Point, and on White Mesa. The displacements are of the order of 100 feet, and a maximum of 200 feet is recorded. Babenroth and Strahler (1945) call attention to the pre-lava age of most of the faults and suggest that some of the structures were resequent grabens bordered by fault-line scarps and that the grabens show a regional alignment closely related to that of the folds. On the basis of these features a rather ancient faulting is implied.

Many such grabens may be buried by the lavas south of the region where they are now seen so clearly. Beyond the limit of the lavas, 6 miles west of Leupp, a rather small graben can be seen. The faults trend north, and the displacement amounts to only 12 feet.

GEOMORPHOLOGY

EROSION SURFACES OF THE LITTLE COLORADO

Statement of the problem.—The geomorphic problem is one of erosion. The most obvious conclusion is that flat and gently inclined beds of variable resistance and the activity of the master stream, the Little Colorado River, control erosion. Truncated beds, low cuestas, and strip slopes are features of the extensive lowland which in places stretches to cliffs on the distant horizon. Plate 3 gives a limited, though characteristic, view of the erosion surfaces.

The main object of the present study is to relate the erosion surfaces to structure, to distinguish interrupted cycles of erosion or multiple surfaces if they exist, to determine their ages and their relationships to the San Francisco volcanics, and to determine if local crustal movements have occurred during the development of the surfaces. Several distinct erosion surfaces were recognized, and their distribution was charted (Pl. 4). This map should be compared with the geologic map of the same area (Pl. 1) for the relation of erosional surfaces to the different formations and to structure.

During the past 20 years many geologists have paid particular attention to the broad plains of erosion that extend out from the abrupt fronts of mountains in arid regions. The carved plain surfaces have been called "pediments", and the term has become well established in geologic literature. The erosion surfaces in the valley of the Little Colorado are characteristic pediments, and, as surfaces that have formed across sedimentary beds of different inclination and of different resistance to erosion, they are pediments with special characteristics. It is therefore necessary to review briefly the concept of pediments before treating the distinguishing features of those of the valley of the Little Colorado.

Erosion surfaces and the concept of pediments.—Pediments are gently inclined

planate erosion surfaces carved in bedrock and generally veneered with fluvial gravels. They have been widely recognized in arid regions (Bryan, 1925; 1933; Blackwelder, 1931; Johnson, 1932; Gilluly, 1937; Howard, 1942). Pediments occur between mountain fronts and valley or basin bottoms (Fig. 3) and commonly form extensive bedrock surfaces over which the erosion products from the retreating mountain fronts are transported to the basins. Slope is greatest near the mountain front, where gradients may be 300 to 500 feet per mile. Valleyward, the slope becomes sensibly flat, although the gradients may actually be 20 feet per mile. Thus, the profile of a pediment is gently concave upward. Small alluvial fans and talus cones at the mountain front as well as sheets of fluvial gravel are transitory features. Fluvial gravels have commonly been described in connection with pediments, yet gravels do not need to be present. The type of rocks being eroded will determine the texture of the erosion products.

Howard (1942) reserved the term pediment for the portion of the surface that is cut in bedrock and proposed the term peripediment for the erosion surface over skirting alluvium. He combines the two under the term pediplane.

The relationship of pediment and peripediment during development of the pediplane is illustrated in Figure 3 under three conditions: when the base level (A) is constant, (B) is being lowered, and (C) is being raised. Cross section A shows a pediplane forming as a slope of a tributary to a master stream, the base level. In this section alluvium is shown in the downslope area, but after its deposition the master stream has remained at a constant level and pediment cutting in the tributary continued. With the continued retreat of the mountain front the pediment is lengthened, its declivity is gradually lowered, and the peripediment once formed remains practically unchanged. The development of extensive peripediments is rare under the condition of a constant base level.

A rejuvenated master stream incurs active erosion over the entire pediplane and only ephemeral deposits will be formed (Fig. 3B). Under such a situation a new pediment surface would develop to the lower base level and work its way headward. Sediments resulting from the process would be largely removed by the master stream, and peripediment development would remain subordinate.

Pediments may form as alluviation of the valley floor occurs, and the condition is one of a rising base level (Fig. 3C). The surface slopes are markedly flattened due to headward extension of the pediment and building up at the base level. Due to headward erosion of the pediment and aggradation at the base level, the peripediment encroaches and increases conspicuously in area. The cut surface preserved beneath the alluvium has a profile which is convex upward—the opposite curvature from the profile of a pediment. This buried surface has been called the suballuvial bench by Lawson (1915). In regions of rising base level the pediplane will be made up for the most part of a peripediment, and the pediment as a near-mountain zone cut on solid rock is sometimes overlooked.

SPECIAL FEATURES OF PEDIMENTS IN THE VALLEY OF THE LITTLE COLORADO RIVER

Pediments on inclined strata.—The general strike of the beds parallels the course of the Little Colorado River. The beds on the west side dip toward the river, and

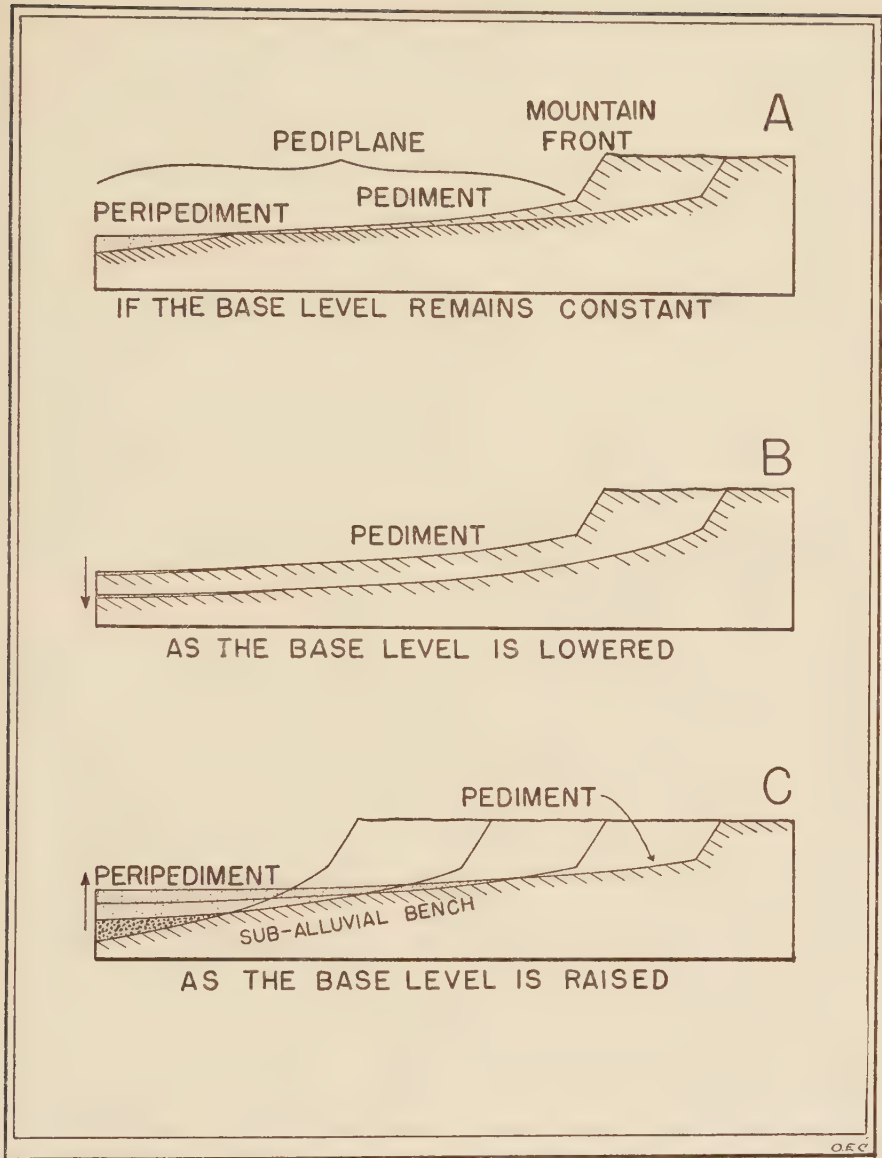


FIGURE 3.—*Relation of pediment to peripeditment*

those on the east side dip away from the river. Further, the beds on the west side are largely the resistant sandstones of the Moenkopi formation and the sandstones and limestones of the Kaibab formation, whereas the layers to the east are mainly the soft shales and marls of the Chinle formation. Hence, the pediments grew westward slowly over resistant materials and rapidly to the east over easily eroded beds. Here, then, is an excellent opportunity to observe and describe the sequence

of forms in an arid cycle of erosion that occur over sedimentary beds of different attitude and of beds that offer differential resistance to erosion.

Strata dipping gently upstream.—To facilitate explanation consider first a pediment growing back from a constant base level into a region of sedimentary rocks that are gently inclined in the opposite direction to stream flow (Fig. 4). One stratum is represented as resistant to erosion, and the others as yielding readily. The mountain front retreats by parallel slope recession, and the pediment surface is progressively altered from early, short, steep slopes to late, long, gentle ones. If the base level remains constant, as is assumed, the regional relief may remain the same until the highlands are destroyed, and the sequence of surface features will be essentially bound up with profile changes. As the retreating front passes the resistant layer, the smooth profile is interrupted (Fig. 4, Blocks I and II). The resistant formation serves as an effective base level for stream activity above it. The master stream into which run the smaller streams is base level for drainage below the resistant strata. The knickpoint caused by the resistant beds gradually lowers and moves headward. Down the slope from the knickpoint pedimentation rapidly reaches stability, but headward the constant regrading of slopes to a changing base level results in widespread dissection with limited pediments extending back from the streams. Eventually the knickpoint is lowered until the profile is continuous across the resistant strata (Fig. 4, profile C and block III).

The interfluvial areas are retarded in development (Fig. 4, profile A). Below the resistant bed, as the mountain front retreats, a pediment forms to the base level and heads against the resistant layer which forms the front of a cuesta. Upslope from the cuesta the surface is drained by gullies that reach headward from the front of the cuesta or that flow into the main tributary streams. Gradation is slow in this retarded headland, and playas may be impounded locally behind the cuesta (Fig. 4, block II). Finally, dissection progresses into the region either by retreat from the cuesta front or laterally from the valleys of accelerated erosion. The cuestas are by-passed by the general surface, and the retarded interfluvial profile becomes continuous with main tributary profiles. Thus profile C becomes the general profile of the pediment to its constant base level. Remnants of the cuesta may still be present and would be called inselbergs.

If the beds are horizontal, retarded headlands with playas and local back slopes would probably not develop. Pediments upslope from the resistant escarpment would be temporarily graded to the knickpoints of the headward-growing notches in the escarpment, later to be dissected and regraded as the lower surface grows into the highland along major stream channels. Eventually here, too, a profile will develop to the controlling constant base level comparable to profile C.

Strata dipping gently downstream.—In regions where sedimentary beds dip in the same direction as the streams flow, the details of surface forms will appear about as shown on Figure 5. When the retreat of the mountain front lays bare the resistant stratum the profile of fastest erosion will be along the main stream channels (Fig. 5, profile B). Downstream from the resistant zone the pediment will be controlled by the constant regional base level (here the Little Colorado River) and will head against the resistant layer. A strip-plane will form first over the resistant bed and

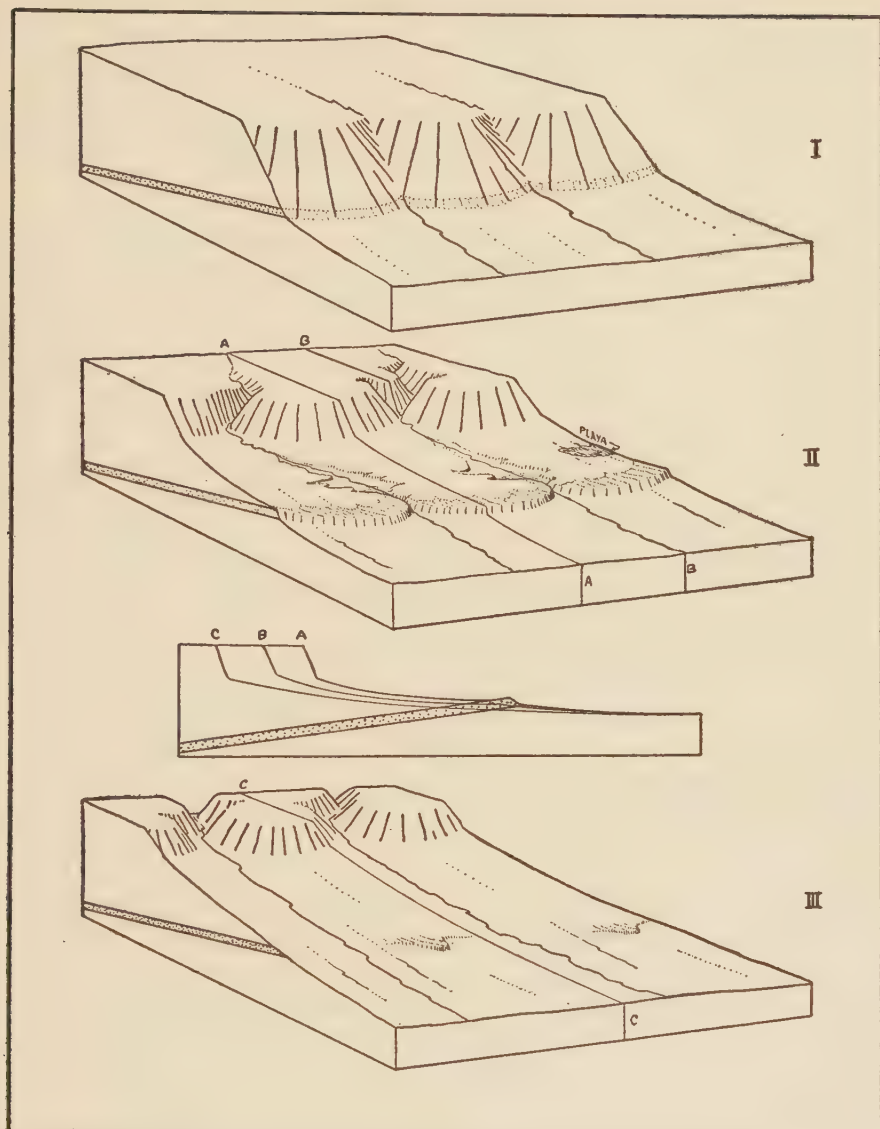


FIGURE 4.—Profile development with beds dipping gently upstream

then a narrow canyon along the stream. A series of knickpoints will form in "rapids" fashion, if the resistant member is made up of a number of beds of considerable thickness, and in working headward will cut through the resistant stratum. Upstream from the resistant zone small pediments will form and will be dissected as each knickpoint migrates headward. Finally, a profile controlled by the regional base level will develop. Interfluvial areas will again be the site of retarded erosion (profile A). Downslope pediments will form to the constant base level and head

against the resistant beds. The resistant strata may become an extensive strip slope, only locally gullied and scoured, and the headland pediments will be graded to the extensive strip slopes. As the general surface is lowered and approaches Profile C, the resistant zone is by-passed and mostly truncated by many drainage lines, and low inselberg remnants of the cuervas facing upstream may remain (block III).

Cycle of erosion in inclined strata.—The arid cycle of erosion as reported by Davis (1905) begins with a series of valleys down-folded or down-faulted between intervening highlands. The sequence of forms through youth, maturity, and old age takes place with a rising base level due to an alluviation of the basins as the mountain fronts recede. To keep the features of the cycle simple, the rocks were considered homogeneous. Through youth, relief is at a maximum, and independent drainage basins with local base levels exist. Relief is reduced in maturity and divides are locally destroyed as the drainage and profiles of two or more basins become integrated. With continued lateral and headward growth of the alluvial piedmonts and pediplanes the mountains that once stood between the basins become irregular inselbergs. In old age pediplanes are extensive and relief is low. Highland areas are destroyed, and only scattered inselbergs remain. Drainage of an entire region may have a common base level and for the most part profiles are very near equilibrium or ultimate gradation.

The changes from independent drainage basins and local base levels to integrated drainage and a common regional base level are the principal criteria for designating the stages of youth, maturity, and old age in Davis' arid cycle of erosion. Since these features are not clearly applicable to the erosional forms in the region of the Little Colorado other criteria must be summoned. A deductive consideration of the form of profiles through the sequence of development makes possible the designation of cyclic stages, which correspond rather closely to those already described in Figures 4 and 5.

Youth is the stage wherein longitudinal profiles are interrupted, and migrating knickpoints are present. Only the lowest pediment is graded to the regional base level. Others higher on the profile are graded to resistant beds in the drainage. Pediments are characterized by their limited extent and relatively steep slopes. Headward extension of planed surfaces is rapid and most pronounced along principal drainage channels. Retarded headlands behind cuervas, zones of dissection, and extensive strip planes abound where resistant beds crop out (Fig. 6).

In maturity the knickpoints have been destroyed, and longitudinal profiles are continuous. The pediment surface has by-passed resistant zones leaving subdued remnants of cuervas in the interfluvial areas. The pediments have merged laterally to form extensive planed surfaces. The zone of most active erosion is immediately in front of the retreating mountain front where the steepest part of the profile exists. The entire mature profile is dominated by the regional base level.

In old age the extensive pediplanes are lowered until they have approached the ultimate profile of gradation. Steep slopes of active erosion are absent, and highland areas have been destroyed (Fig. 6). Thus, the relief of youth and maturity is lost.

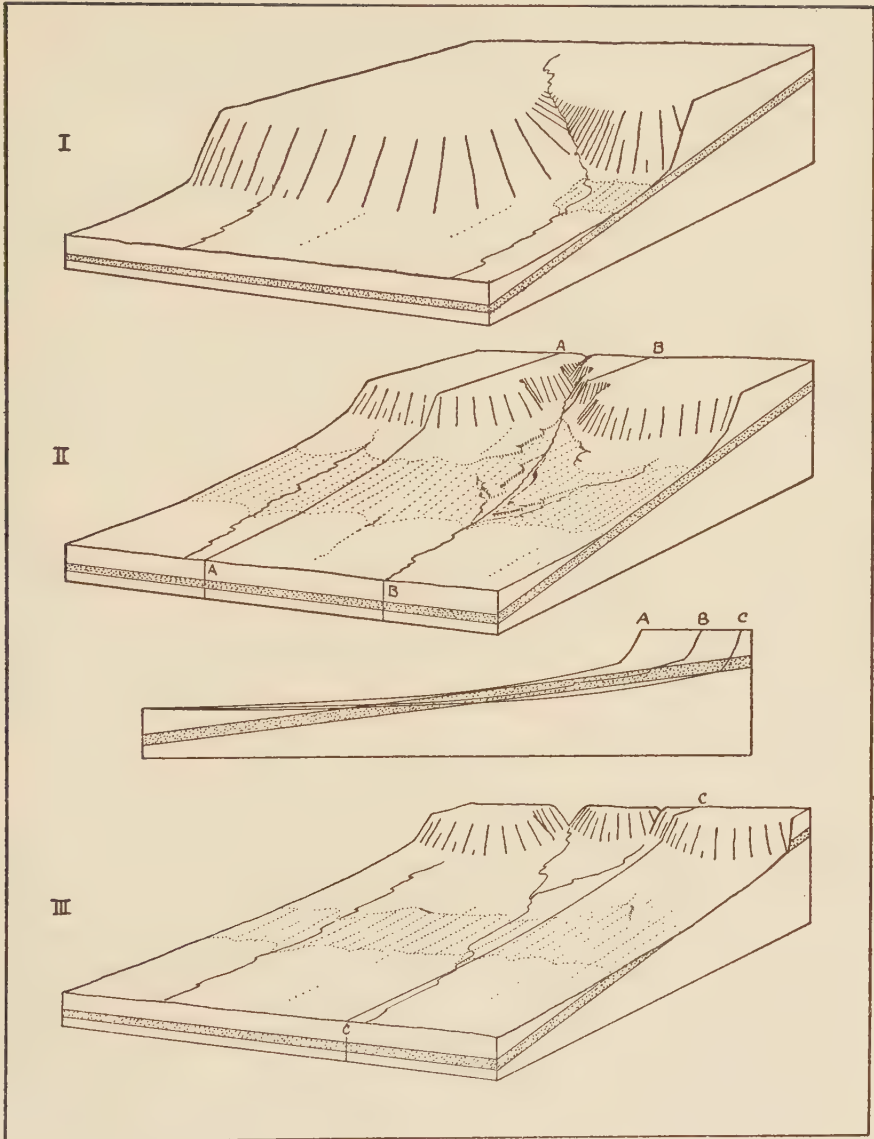


FIGURE 5.—*Profile development with beds dipping gently downstream*

The general declivity of the surface will be near the profile of equilibrium which is controlled by climatic conditions and gradient.

If the master base level is lowered, an epicycle will be imposed on the above sequence of events. Dissection and limited local pedimentation will ensue until the regional base level is stabilized after which the new pediments will expand, adjusted to the lower base level. The base level is the most important control during a cycle

of erosion, for its behavior, whether stable or fluctuating, must be reflected in the surface features of the region affected by it.

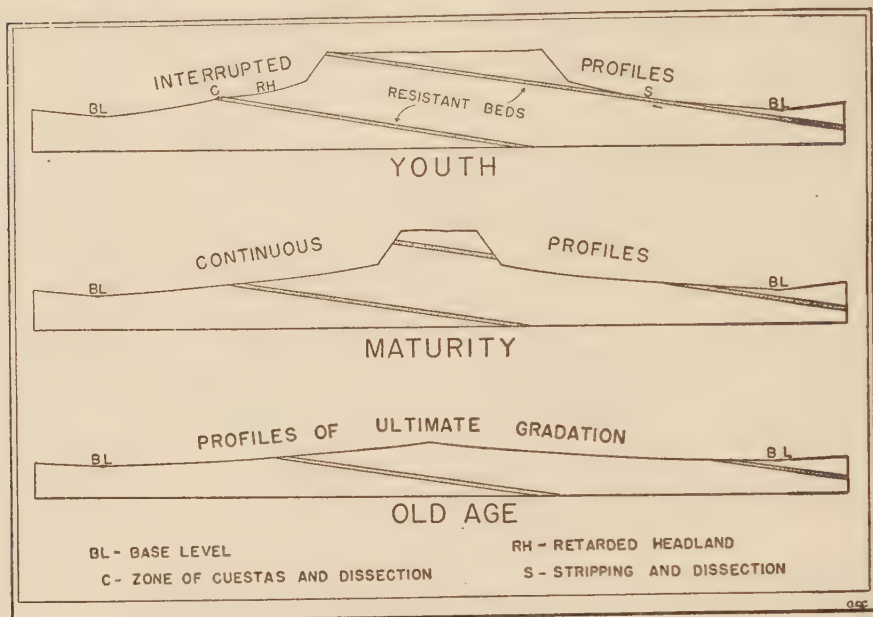


FIGURE 6.—Pediment cycle of erosion in a region of inclined beds

PEDIPLANES IN THE VALLEY OF THE LITTLE COLORADO

General characteristics.—The pediplanes adjacent to the Little Colorado River consist mainly of pediments. Only limited peripediments exist as gravel-capped interfluvial tablelands near the river. The gravel fills, over which the peripediments have formed, are in most places from 4 to 8 feet thick and consist mainly of rounded chert pebbles. In general, gravels on the pediments are not thicker than the depth of scour of floods. In a very few places, however, gravel fill reaches a thickness of 25 feet. The Little Colorado River apparently has been able to carry away readily most of the sediments that have been brought to it from its flanking pediments.

In the region of this study three principal pediplane surfaces are suggested. Projection of the surfaces from either side of the Little Colorado River Valley to a line of intersection indicates that the regional base level has lowered and become stable at least three times. Each time stability of base level has endured for a shorter and shorter time. In each of the three positions the Little Colorado River as the master stream has followed a course nearly directly below its previous course. The lowest surface is now being developed to the present position of the Little Colorado River and to the large, tributary Tusayan Washes that enter from the northeast (Fig. 1). This surface will be called the Little Colorado pediplane. In the Wupatki area remnants of an intermediate surface are approximately 200 feet above the river. These pediment remnants stand as truncated interfluvial table lands between the

abrupt arroyos that drain the area. The surface represented by the remnants will be called the Wupatki pediplane. A remnant of a surface 600 feet above the Little Colorado River is preserved beneath a thin basaltic flow at Black Point, 9 miles north of Wupatki National Monument. Other high remnants occur elsewhere, and the surface indicated by them is referred to as the Black Point pediplane.

Plate 4 presents the general distribution and character of the pediment remnants and other erosional features in the area studied.

Black Point pediplane.—The Black Point pediplane is named from Black Point about 9 miles north of Wupatki where it is preserved beneath basaltic lava. The surface over which the lava flowed is a pediment sloping approximately 20 feet to the mile toward the Little Colorado River and heading against the San Francisco highland to the southwest. It was developed for the main part over the red sandstones and shales of the Moenkopi formation which are inclined in the same general direction and about the same amount as the pediment. The surface passes uninterrupted over the Black Point monocline and truncates the beds that are bent down sharply. The relation of pediment surface to the structure of the underlying beds is shown clearly here where the pediment has been protected beneath the lava cover while adjacent areas have been lowered by subsequent erosion. Northwest of Black Point (Pl. 4) the destruction of the Black Point surface has begun. Here the surface is represented by flat-topped interfluves on the Moenkopi formation. Lava bounds this area of the old surface on three sides and has retarded destruction by the streams that drain this section. Thus, it is believed that dissection of the pediment has gone on very slowly here.

Farther northwest, downstream on the Little Colorado, remnants of the Black Point pediplane have been destroyed in the deeply dissected and widely stripped area of the Marble Platform (Fig. 1). As the gorge of the Little Colorado deepens, toward its junction with the Colorado River, the general surface of the region rises steadily toward the Coconino and Kaibab plateaus. This surface of the Marble Platform is a vast stripped and dissected plane on the Kaibab formation rising well above the Black Point pediplane. It is assumed, therefore, that the Little Colorado River was flowing in a deep canyon across most of the Marble Platform when the Black Point surface was forming in the upstream regions.

Southward from Black Point, over White Mesa and Antelope Prairie, the pediment surface has also been destroyed. Stripping down to the resistant Kaibab limestone has occurred, and the Kaibab in turn has been dissected by the tributaries of the Little Colorado. The dissection is less pronounced westward over the nearly flat plain of White Mesa. The deep entrenchment at the front of the monocline has not cut far headward except along large tributaries. On to the south, from Woodhouse Mesa to Merriam Crater (Pl. 1), Stage 1 lava flows can be traced almost without a break. They emerge from beneath the younger flows and are seen on a continuous surface cut over Moenkopi sandstone and shale. This surface is clearly a continuation of the Black Point pediplane.

Southwest of the area mapped the Kaibab formation rises steadily toward the summit of the San Francisco Plateau. Here Highway 66 ascends a gradual slope which suggests an extensive surface stripped to the resistant Kaibab. However,

the dip of the beds does not everywhere coincide with the surface. Local swells and sags in the structure are truncated. At the contact with the softer Moenkopi the surface is preserved as flat-topped obsequent cuestas in the contact zone. The position and elevation of this erosion surface suggests that it is a continuation of the Black Point pediplane and was preserved because it was developed on resistant beds. Subsequent erosion has only locally dissected and stripped it, as at Canyon Diablo, Canyon of the Padre, and at Walnut Canyon.

East of the Little Colorado opposite Black Point, shales and weak sandstones predominate, and the Black Point pediment has been preserved only on the most resistant rocks. A resistant bed near the top of the Chinle formation forms the crest of a long somewhat irregular cuesta that faces the Little Colorado River. At several places this cuesta has been breached, and at other places it forms the "mountain front" for pediments of the present valley floor, but its flattened, gravel-capped crest stands as a narrow remnant of the older and higher Black Point surface (Pl. 4, profile A'-A). Farther east the crests of the Wingate and Navajo cliffs are pediment remnants of the Black Point pediplane. North of Dinnebito Wash, a narrow peripediment remnant of the Black Point surface forms the divide between the drainage to Dinnebito Wash and to the Little Colorado River (Pl. 4, profile B-A).

The surface of this remnant is continuous with that of the crest of the cuesta and is developed over gravels which reach an unusual thickness of 25 feet. The length of the ridge is approximately 5 miles, and it is extremely narrow throughout. Extensive gullying along the flanks emphasizes attack by vigorous erosion. Possibly the thick gravel capping may be in part responsible for the local preservation.

The preservation of the peripediment remnant north of Dinnebito Wash is fortunate because the slope of the Black Point surface east of the Little Colorado can be determined by means of it. The declivity of the surface is much the same as that beneath the lavas of Black Point, and projection of the two surfaces shows that the master stream of the region was approximately 600 feet above the present course of the Little Colorado River.

Robinson (1907) reported the erosion surface under the lava flow at Black Point as a local remnant of a widespread "peneplain" covering thousands of square miles in the Plateau country. In a later report (1913) he believed the surface to be the product of Dutton's "Great Denudation" following the first period of faulting at the close of the Miocene. During the faulting the large elements of the plateau province were outlined, according to Robinson, much as at present. He dated his "First period of volcanic activity" in the San Francisco Peaks area as Late Pliocene because the lavas had poured out upon the extensive surface that resulted from the "Great Denudation", or "peneplain cycle of erosion", which, he assumed, required most of the Pliocene epoch.

In the immediate vicinity of Black Point there seems to be little information about the age of the Black Point pediplane except that it is older than the Stage 1 lavas. Robinson's dating had no stratigraphic or fossil foundation, and, therefore, it becomes necessary to seek other evidence for age determination.

North of the Little Colorado River upstream from Leupp is a region of Tertiary volcanic and sedimentary rocks known as the Hopi Buttes (Fig. 1). Various aspects

of this area have been reported by Gregory (1917), Williams (1936), and Hack (1942). Williams (1936) recognized that the lavas and lacustrine sediments of the Hopi Buttes accumulated on an erosion surface of low relief. Vertebrate fossils from the sediments include fish, birds, amphibians, beaver, and camels and indicate an age of Middle and Late Pliocene. These beds are included in the Bidahochi formation of Hack (1942). The formation reaches a thickness of 400 feet and is made up of water-laid marl, calcareous tuff, clay, and sand.

A traverse from the Little Colorado River at Winslow northward into the Hopi Buttes shows a series of pediment levels much the same as those in the regions downstream near Wupatki and Black Point. At Winslow the river is at an elevation of approximately 4850 feet, and to the north the surface rises steadily. The first 250-foot rise is over an irregular gullied surface of dissection and rolling sand dunes beyond the surface that is evidently the Little Colorado pediment. Then for 7 miles the ascent is over the general surface of a pediment mantled with 4 to 6 feet of gravel and rising with a general slope of 20 feet to the mile. This erosion surface from all characteristics is the same as the Wupatki pediplane downstream. It heads against a resistant horizon near the top of the Chinle formation, and 200 feet higher a pediment surface (600 feet above the Little Colorado River) continues on into the Hopi Buttes. This highest pediment is believed to be a part of the Black Point pediplane and as a general surface rises to each of the local buttes which stand above it as inselbergs. The Black Point pediplane heads far back in the mesa and plateau elements of the region and truncates the Bidahochi formation in many places, as, for example, at Castle Butte where the elevation is 5450 feet. Thus, the Black Point pediplane is more recent than the Pliocene lavas and sediments of the Hopi Buttes and is probably latest Pliocene or early Pleistocene.

The "Hopi Buttes Peneplain" of Gregory (1917), referred to by Hack (1942), is the surface on which the lavas and sediments accumulated. During the development of the Black Point pediplane the lava-capped areas of the Hopi Buttes Peneplain formed a highland into which pediments grew from the Little Colorado River. The Black Point surface reaches lower and is younger than Gregory's "Hopi Buttes Peneplain" and cannot be correlated with it as suggested by both Gregory (1917) and Hack (1942). Since the Stage 1 lavas of the San Francisco field spread over parts of the Black Point pediplane which is younger than the surface beneath the Hopi Buttes lavas, the San Francisco lavas are clearly more recent than those of the Hopi Buttes.

The Wupatki pediplane.—Immediately south of Black Point and along the northern margin of the Wupatki Basin there are numerous remnants of a pediplane surface 150 feet above the river. This surface is the Wupatki pediplane (Pl. 4, profile A'-A). To the west it heads against Moenkopi beds, which are upturned sharply in the Black Point monocline, and is developed over Moenkopi and Shinarump beds. The surface here is a pediment with only a thin mantle of gravel, and it slopes toward the Little Colorado River with a gradient of approximately 30 feet per mile. The beds are inclined eastward slightly more than is the surface, and they are therefore truncated. Near the head of the pediment the beds are locally wrinkled into a small syncline and anticline, both of which are truncated by the surface. Across the river, along

the line of cross section A'-A in Plate 4, the Wupatki pediplane rises to the distant Chinle cliffs. The declivity of the surface is comparable with that west of the river. Near the river the surface is locally a peripediment over gravel that reaches a maximum thickness of 20 feet. This remnant is now an inselberg by-passed on both sides by a still lower surface.

Along the southern margin of the Wupatki basin the Wupatki pediplane is preserved beneath basaltic lavas of Stages 2 and 3 (Pl. 1). Here the surface is comparable in slope and elevation with that beneath Black Point and is a pediment developed on Moenkopi beds.

The river crosses the Tolchaco anticline in a canyon zone from Tolchaco to Black Falls. Along this zone the Wupatki pediment approaches the top of the canyon walls from both sides. West of the river the surface heads against the highland of the Black Point surface capped with lava. The Wupatki pediment is well preserved here, giving way to deep dissection only near the river. Much of the Wupatki surface west of the river is covered by lavas ranging in age from Stage 2 to Stage 4.

East of the river many interfluvial areas are remnants of the Wupatki surface, but dissection is fairly advanced. In the canyon zone of the Little Colorado the Dinnebito Wash enters as one of the largest tributaries. This tributary was well established before the Wupatki pediplane had been eroded because the Wupatki surface extends along the flank of the long Black Point pediplane remnant north of Dinnebito Wash (Pl. 4). Here the pediment slopes toward the wash rather than toward the Little Colorado, and indications are that during this stage a surface, tributary to the Wupatki of the Little Colorado, developed far up Dinnebito Wash. Further, the Wupatki remnant along the north side of Dinnebito emphasizes the concept that the Wupatki pediplane was a youthful surface with interrupted profiles. It reached beyond the cuesta of the Chinle Cliffs and developed a retarded headland between the cuesta and the Wingate cliffs. Still, the Wupatki pediplane was far enough advanced to have extended widely over the resistant Moenkopi beds west of the river.

West of Leupp the Wupatki pediplane was formed over Moenkopi beds, and it heads against the resistant Kaibab over on the Tolchaco anticline. The major tributary to the Little Colorado in this area is made up by the merging of Walnut Creek, Padre Creek, and Diablo Creek. The latter two flow in gorges 150 feet deep through the anticline and merge near the axis of the fold (Pl. 1). They seem not to have been deflected by the anticline that stands across their paths, and, therefore, these courses were developed on a higher and older surface than the Wupatki.

North of Leupp the road to the Hopi Villages ascends a long remnant of the Wupatki surface. In the northwest cross section this spur is distinctly asymmetrical. Its northwestern flank is abrupt and drains to the Little Colorado River. To the southeast the slope is gentle as the spur forms the head of a pediment grown back from the present position of Polacca Wash (Pl. 4). The top of the spur is flattened and capped with gravel. The gravel veneer thins from 15 feet to $2\frac{1}{2}$ feet upslope. This Wupatki pediplane remnant is $4\frac{1}{2}$ miles long. Toward the head the slope is 50 feet per mile, and it flattens downslope to 20 feet per mile.

It is possible to make more projections of profiles of the Wupatki pediplane and to restore the surface more completely than the Black Point. The slope of the remnants of the Wupatki surface would require a master stream 70 feet above the Little Colorado at Leupp, and 150 feet above the river at Black Point. This would produce an average gradient for the base-level stream of 10 feet per mile, and the early channel would be approximately along the same course as the present Little Colorado.

The Wupatki surface was developed in the erosion interval between the lava flows of Stage 1 and Stage 2. It is older than the acidic volcanic rocks of the San Francisco Peaks (Table 1), which were later subjected to glaciation. Hence, the Wupatki pediplane is earlier than the first glacial stage in the San Francisco Mountains and is probably early or middle Pleistocene.

The Wupatki "B" pediment.—The Indian ruins of Wupatki National Monument stand on a remnant of a pediment which accords in level with other flat-topped interfluvial remnants in the Wupatki basin (Pl. 3, fig. 2). The surface represented by these remnants heads against the monocline and against the lava-capped Woodhouse Mesa. At its head it is slightly lower than the Wupatki pediplane beneath Black Point. The slope of the lower surface toward the Little Colorado River is more inclined, and the remnants of the surface are only 75 feet above the river. This pediment will be called the Wupatki "B" pediplane (Pl. 4, Sec. B-A). It was observed well developed only in the Wupatki basin, but suggestions of it appear west of the river between Black Point and Cameron. East of the river the rapid development of the still lower Little Colorado pediment has left no certain remnants of it. In age it is clearly intermediate between the Wupatki surface and the Little Colorado surface. However, the Wupatki "B" pediment may correlate with a part of the Little Colorado pediplane where the latter is developed upstream from the canyon zone in the region of Leupp.

The Wupatki "B" surface is in such a position as to suggest that it, together with the Little Colorado surface upstream from the canyon zone, represents the first period of stability in the profile of the Little Colorado River after entrenchment of the Wupatki pediplane began. The surfaces could not have been continuous but would have been separated by a canyon zone nearly as long but not so deep as the present one. Subsequent lowering of the profile to the present level downstream from the canyon zone would have occurred while knickpoints were migrating upstream and were deepening the canyon zone. The Little Colorado pediments upstream from the canyon zone would thus become a retarded headland for the stream activity in the Wupatki basin. The Wupatki "B" pediment owes its existence to actively eroding tributaries flowing from the San Francisco highlands, and these tributaries, if influenced by a short period of stability in the position of the master stream, would have carved the Wupatki "B" surface.

Little Colorado pediplane.—The Little Colorado pediplane is the surface now developing to the present position of the Little Colorado River. It is an extremely youthful pediplane and has extended only into readily eroded materials. The absence of dissection makes it difficult to determine the extent of peripediment development, but a pediment surface probably predominates. The Little Colorado surface can best be described in three sections along the river: (1) the region up-

stream from Cameron to the canyon zone south of Black Falls, (2) the canyon zone from south of Black Falls to a point 16 miles upstream where the valley opens out again at Tolchaco, and (3) from the head of the canyon zone upstream to Leupp and the Polacca Wash tributary (Pl. 4).

At Cameron the Little Colorado River enters the narrow gorge in which it continues to its junction with the Colorado River in the Grand Canyon. Yet, upstream from Cameron the river flows along the western side of a broad open valley with gentle pediment slopes rising eastward to the cuesta of the Chinle Cliffs. Although the region to the west is deeply dissected the resistance of the Moenkopi and Shinarump beds has so inhibited pediment growth that only limited pediment embayments have extended up tributary streams. To the east an extensive pediment surface has developed over the soft lower Chinle beds and heads against the cuesta formed by the resistant upper beds of the formation. Along some of the larger tributary streams the surface steepens abruptly and reaches beyond the cuesta front into the retarded headland. The general youthful picture of limited pediment development into regions of resistant rock and extensive growth into the soft beds of the Chinle formation characterizes this entire section. In the southern part of the section, *i.e.*, from Black Point to the canyon zone south of Black Falls, the Little Colorado pediplane has by-passed and isolated inselberg cuestas of Moenkopi and Shinarump rocks. The summits of the inselberg cuestas are remnants of the Wupatki pediplane (Pl. 4).

The river passes through a 16-mile canyon zone that extends from Tolchaco nearly to Black Falls. This is a zone of vertical dissection through the resistant beds of the Kaibab formation, and lateral pediment development has not begun. Upstream from Grand Falls the narrow canyon has been filled with alluvium behind the lava dam of Stage 4 lavas (Pl. 1; Pl. 2, fig. 2). Over the top of this alluvial fill the river has found its way around the end of the lava dam and now plunges 175 feet back into its own gorge (Pl. 2, fig. 1).

Dinnebito Wash debouches through a narrow gorge into the Little Colorado in the canyon section. Upstream, Dinnebito Wash is on the soft beds of the Chinle formation, and an extensive pediment surface has grown. It has the appearance of a tributary surface to the general Little Colorado pediplane.

In the region from the canyon zone to Leupp the pediment surface has grown back from the river, again mainly to the east. The youthfulness of the Little Colorado pediplane is realized when it is noted that upstream from the canyon zone the pediment is graded to its master stream at an elevation of 380 feet above the same surface downstream, opposite Black Point. The upstream region can be regarded as a retarded headland along the master stream, held back in development by the existence of knickpoints in the canyon zone along the longitudinal profile of the Little Colorado River. Due to a lowered base level, the pediplane in the upstream area probably would now have been widely affected by dissection if the migration of the knickpoint had not been checked. The headward migration of knickpoints through the canyon zone has been interrupted by the lava dam of Grand Falls and deep sediment fill behind it.

Polacca Wash enters the river at Leupp, and the general pediplane to the master stream merges with that of the tributary.

The obvious recent geologic age of the Little Colorado pediplane emphasizes the recency of Stage 3 and Stage 4 lavas which are on it. Lavas of both stages have followed down channels that are headward extensions of streams flowing over the youngest pediment. Pedimentation and dissection had advanced to a stage wherein the topography was comparable with the present before Stage 3 lavas were extruded. From glacial studies in the San Francisco Mountains, Sharp (1942) concludes that Stage 3 lavas are post-Iowan-Wisconsin.

LITTLE COLORADO VALLEY AND THE GRAND CANYON

Concepts of Grand Canyon morphology.—The sequence of events in the cutting of Grand Canyon has long been the concern of many investigators in the plateau region. In the first approach to the problem Powell (1875, p. 198) states that, "... the system of drainage was determined antecedent to folding and faulting." He envisioned a long period of prodigious erosion as the region was slowly raised against the Colorado River and its tributaries. Dutton (1882), agreeing with the concept of antecedency, described an interrupted uplift of the region resulting in two great cycles of erosion. "The Great Denudation", he postulated, was started by early Tertiary uplift and continued until Pliocene time when renewed uplift resulted in the "Canyon cycle" of erosion. This has been in progress to the present. Davis (1901) followed Dutton in the concept of two cycles of erosion; he contended that the Colorado River was not antecedent to the structures but was in part a consequent stream determined in its initial position by the slopes of an ancient depositional surface. The depositional surface resulted from the accumulation of Tertiary sediments following the Laramide revolution. He used the term "plateau cycle" in place of the great denudation.

The great denudation was supposed to have resulted in a peneplain, and vigorous erosion in the highlands has since destroyed most of it. However, several surface remnants were noted in the Plateau country and ascribed to the general "peneplain." The surface beneath the lavas of Mt. Trumbull on the Uninkaret Plateau was pointed out by Dutton (1882), and later by Davis (1901). The surface beneath the lavas at Black Point was described by Robinson (1907). The "Hopi Buttes peneplain" beneath lava was reported by Gregory (1917). All were considered local remnants of the regional peneplain of the great denudation.

Based on the previous regional studies Gregory (1933) presented the current concept of the geomorphic history of the Colorado Plateau country. His sequence of events may be summarized as follows:

- (1) After widespread deposition of the Eocene strata regional uplift occurred, and consequent drainage developed on the slopes and inequalities of the uplifted block. The larger streams cut through the Eocene strata and became superposed on the Laramide structures.

- (2) In the erosion that followed (Dutton's "Great Denudation" and Davis'

"Plateau Cycle") Cenozoic and Mesozoic beds were removed. Quoting from Gregory,

"Parts of the present surface of the Kaibab, Kanab, Uinkaret, Shivwits, and Coconino plateaus are thought of as remnants of the plain formed at the end of this first period of erosion."

(3) Regional uplift of 6000 to 8000 feet, probably not all at one time, introduced the "Canyon cycle" of erosion. Erosion has continued to the present.

The erosion surfaces of the Little Colorado as interpreted in the foregoing pages add considerably to the currently accepted theory of the origin of the Grand Canyon; the following pages will be devoted to a discussion of the relationship.

Grand Canyon related to Little Colorado morphology.—The peneplain character of the earliest surface is immediately troublesome in the light of the modern concept of pediments in arid countries, and even to early investigators the nature of the surface appears in doubt, because the notions of antecedency and superposition are not clearly based on detailed geologic maps or on widespread tracing of erosion surfaces. Davis (1901) and later Johnson (1909) described open valleys on the Kaibab Plateau as mature stream valleys residual from the peneplain of the early cycle of erosion. Mature features are not compatible with an old-age surface of the extent ascribed to the peneplain at the end of the great denudation. Strahler (1944) has explained the same open valleys on the Kaibab plateau as due to processes of solution. On the Uinkaret plateau the "peneplain" remnants pointed out by Dutton, Davis, and Johnson were studied by Koons (1945). He described the surface beneath the lava of Mt. Emma, Mt. Logan, and Mt. Trumbull as being a typical pediment with a declivity reaching 300 feet per mile. A modern approach to the problem is one by Moore (1926). He concluded that the form of canyons in the Colorado Plateaus indicates at least one well-advanced cycle of erosion preceding the present, but did not consider the subdued surface to be a peneplain. He believed that the surface in parts of the Plateau Province at the close of the pre-canyon cycle showed unreduced plateaus that rose 2000 feet within a few miles from main drainage lines. He suggests further that the Colorado River had possibly begun to carve the Grand Canyon prior to the beginning of the "Canyon circle".

Regarding the Black Point pediplane of the Little Colorado, the lava-covered erosion surface was probably not a part of an extensive peneplain as was suggested by Robinson (1907), because, as it is traced toward Grand Canyon, it is lost against the higher stripped and dissected Marble Platform. (See Figures 1 and 7.) Also from previous discussion it seems fairly well established that the Black Point pediplane was developed to the Little Colorado upstream from a gorge through the Marble Platform. A comparable situation exists today where the Little Colorado pediments are forming upstream from the gorge of the Little Colorado River, and also where pediments are forming to Dinnebito Wash upstream from its canyon zone (Pl. 4). Hence, at the Black Point stage the Little Colorado was already entrenched in its lower course through the Marble Platform, and the canyon-cutting cycle was well under way in the Grand Canyon. Possibly the Colorado River had accomplished approximately 2000 feet of its excavation of Grand Canyon. (See Black Point stage in Figure 7.)

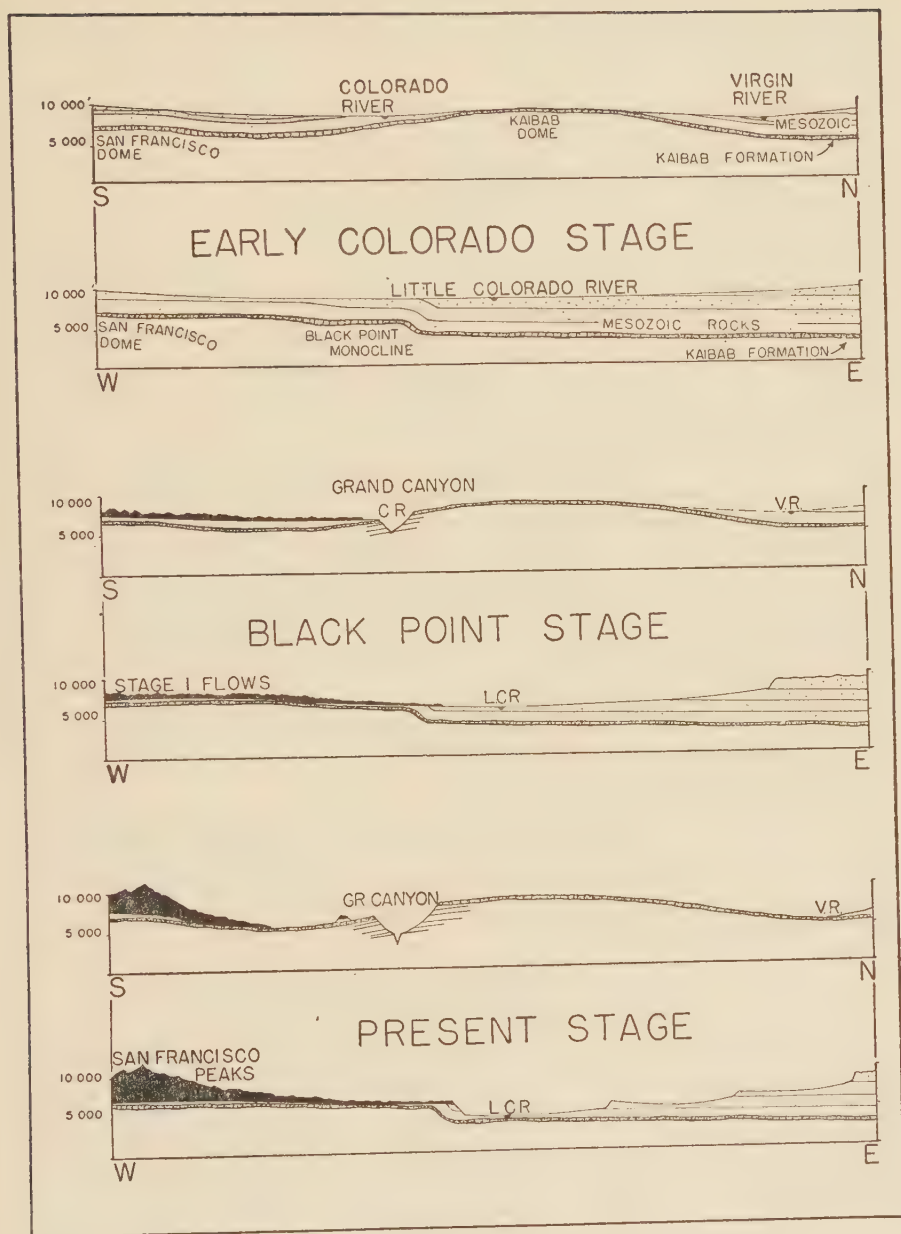


FIGURE 7.—Relation of Little Colorado morphology to Grand Canyon

It is particularly significant that the Grand Canyon was already 2000 feet deep when the Black Point surface was formed because there are no higher remnants of pediments in the entire watershed of the Little Colorado, except far to the east in Black Mesa and in the Hopi Buttes.

The course of the Little Colorado was well established prior to Black Point time. This is evidenced in the position of the river indicated by a reconstruction of the Black Point pediplane.

To the east, the Black Point pediplane heads far back in Black Mesa, and features of an earlier, higher surface may exist there. It has been shown that the Black Point surface developed to lower elevations at a later time than the Hopi Buttes surface described by Gregory (1917) and Hack (1942). The Hopi Buttes surface would indicate a period of advanced erosion prior to the Black Point stage and may represent the early Colorado peneplain of Gregory (1917). Later work may prove that other pediplane remnants such as that described by Koons (1945) on top of the Uinkaret Plateau are parts of the early surface that existed prior to the Black Point cycle. Koons believes the surface beneath Mt. Trumbull extended back from the Colorado River at a time when it was flowing near the level of the Kaibab beds which now form the rims of the Grand Canyon.

The sequence of events in the last part of the geomorphic history, the so-called canyon cycle, is indicated in the valley of the Little Colorado. Uplift after the little-understood early Colorado stage caused rejuvenation and dissection, at least in the area of the Little Colorado. After stabilization of base level the Black Point pediplane was cut. The extensive lateral development and mature profiles of the Black Point pediplane would have required a long period of stability, one most reasonably associated with a long interval between regional uplifts. Renewed uplift caused a second rejuvenation of the region, and after a shorter time of stabilization of the Little Colorado River the Wupatki pediplane was completed. A third uplift may have resulted in the youthful erosional adjustments that are occurring in the region today (Fig. 7, last diagram).

The Grand Canyon has been cut through a highland where extensive erosion has removed all but a few scattered evidences of past erosion cycles. The geomorphic history of the Colorado River might best be established by studying further the sequence of events as shown along the major tributaries such as the Paria, the San Juan and the Virgin rivers.

SUMMARY OF THE GEOMORPHIC HISTORY

(1) The geomorphic events evident in the area of the Little Colorado are probably events of "the canyon cycle" of the Colorado Plateau province and make up the final period in the regional geomorphic history.

(2) The Black Point pediplane is the oldest erosional feature observed in the valley of the Little Colorado. However, prior to the development of this pediplane, another erosion surface existed, viz., the Hopi Buttes surface.

(3) The major structural pattern of the region had been established by Black Point time. The major drainage lines of the Little Colorado and the Colorado rivers existed in much the same courses as at present.

(4) The Little Colorado River as a graded stream provided a constant base level from which the Black Point pediplane grew laterally over a wide area and reached an advanced stage of development. This surface spread across sediments of middle or late Pliocene age and is therefore dated as late Pliocene or early Pleistocene.

(5) After the Black Point pediplane had reached an advanced stage of development, Stage 1 basaltic lavas of the San Francisco Peaks volcanic field flowed over part of the erosion surface.

(6) The region was rejuvenated after Stage 1 lavas. The Little Colorado River cut downward, probably as a result of regional uplift, and the Black Point surface was widely dissected.

(7) When the Little Colorado River established a graded profile the Wupatki pediplane developed. The Wupatki surface reached a stage of late youth in which the lower profiles were continuous laterally over resistant Moenkopi and Shinarump beds as well as the easily eroded Chinle formation. In the headland areas east of the river there was local adjustment to resistant beds.

(8) Stage 2 basaltic lavas which antedated the earliest glaciation in the San Francisco Mountains spread over parts of the Wupatki pediplane.

(9) The region was rejuvenated again probably as a result of regional uplift, and the Little Colorado cut downward approximately to its present position.

(10) In downcutting, the Little Colorado has become graded upstream from the resistant Kaibab formation, where knickpoints in the river profile have formed in the canyon zone across the Tolchaco anticline, and at the upper end of the gorge of the Little Colorado near Cameron. The Little Colorado pediplane has formed to the graded segments of the river. Soft beds have been truncated in the headward growth of the pediments while the resistant beds are dissected and show only limited pediment growth.

(11) Stage 3 and Stage 4 lavas have spread over the irregular dissected surface in this last cycle of erosion. Stream channels followed by lavas are nearly modern in their character.

(12) Scarcely more than 1000 years have passed since the volcanic activity of Stage 4. During that time dissection and pedimentation have made few changes.

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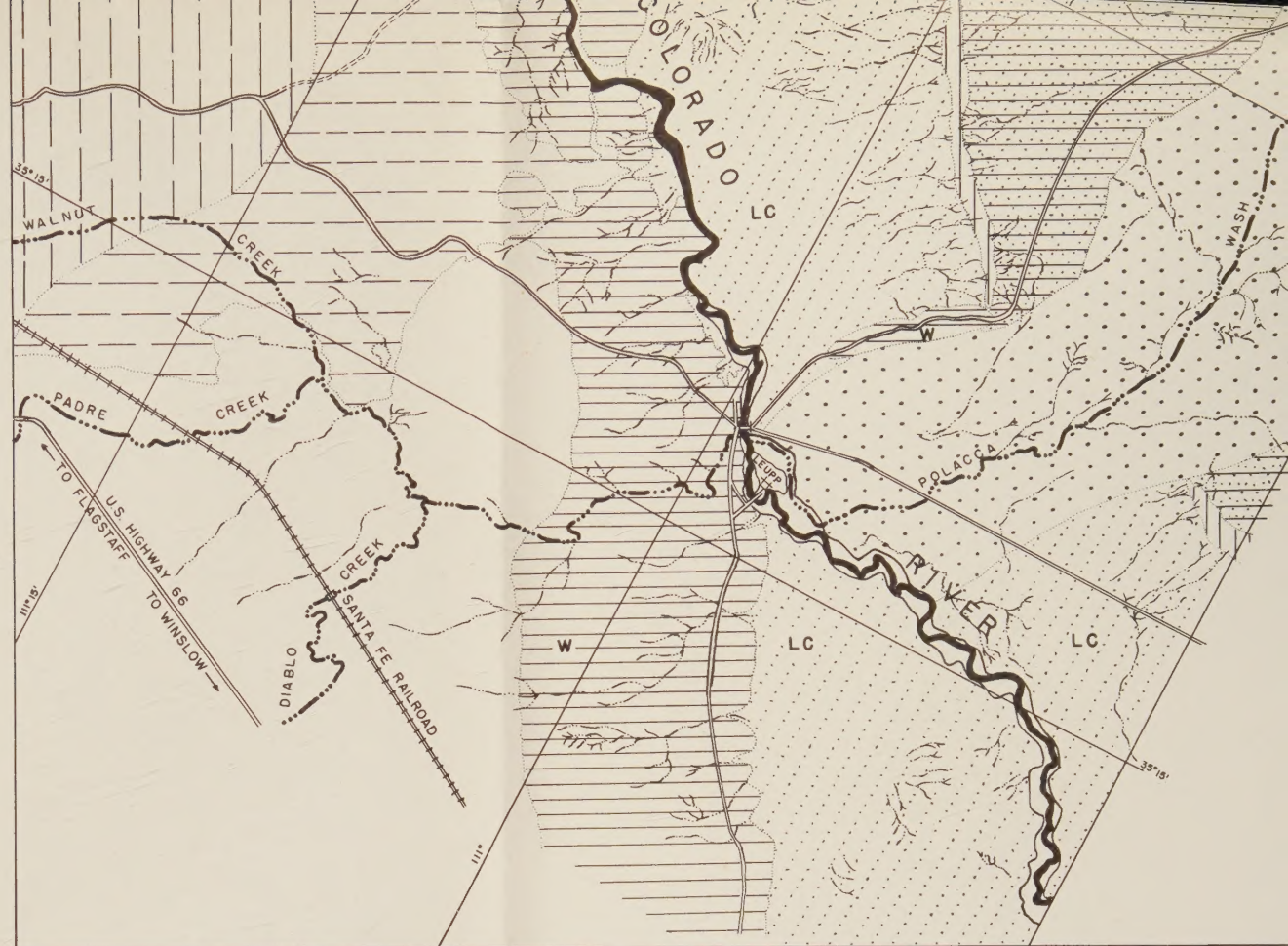
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BLACK POINT PEDIMENT
UNDER LAVA

ORLO E. CHILDS
1946



MAP AND SECTIONS OF EROSION SURFACES OF LEUPP-WUPATKI-CAMERON AREA



CROSS SECTIONS ALONG THE LINES A'-A AND B-A



VERTICAL SCALE IS FIVE TIMES
THE HORIZONTAL SCALE

0 1 2 3 4
MILES

QL BASALT LAVAS
JGC GLEN CANYON GROUP
RC CHINLE SHALES, ETC.
RS SHINARUMP CONGLOMERATE
RM MOENKOPI FORMATION
CK KAIBAB FORMATION

